SOME ASPECTS OF TEST AND DESIGN AT RADIO STATION CKUA

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J.W.Porteous.

Being a summary of some of the work done by the members of the staff of the Department of Electrical Engineering, Dr. H.J. MacLeod, Mr. W.E. Cornish and Mr. J.W. Porteous, under whose care the operation of the station is placed.

Presented to the Committee on Graduate Studies, the University of Alberta, as a partial requirement for the Degree of Master of Science.

University of Alberta
Electrical Engineering Department
Edmonton
March 30, 1933

This is to certify that the undersigned have read and recommended to the Committee on Graduate Studies for ac- ceptance this thesis submitted by J.W.Porteous entitled

SOME ASPECTS OF TEST AND DESIGN AT
RADIO STATION C.K.U.A.

This report is submitted to the Committee on Graduate Studies with the approval of

SOME ASPECTS OF TEST AND DESIGN
AT
RADIO STATION C.K.U.A.

The tests and designs, for the University of Alberta's Radio Station C.K.U.A., included in this paper are part of the work done by Mr. Cornish and myself during 1931 and 1932.

For the most part we did not touch the studio apparatus since it was purchased with the makers guarantee but confined ourselves to the broadcasting station proper. We will then consider only that part of the equipment starting after the studio amplifiers. This includes the lines from the studio to the station, the speech amplifying equipment, the modulators and the oscillating circuit in the transmitter.

Also there will be descriptions of the design and assembly of some of the equipment used in the tests.

EARLY HISTORY:

A short description of the early history of station C.K.U.A. might help to show why it was desirable to carry out these tests. The station was placed in operation on November the 21, 1927 and at that time con-

sisted of a Meisner Oscillator and Heising system of modulation.(See Fig. #1 for diagram.) The lines from the studio to the station were and still are part of the telephone system of the University. Four lines into the station are used for the following purposes. Two for broadcast transmission purposes, one for telephone communication to the studio and the fourth for city telephone. The two broadcast lines with suitable switching arrangements fed into a 50 watt speech amplifier the volume of the signals being controlled by a potentiometer across the line. The speech amplifier was connected by means of a transformer to two 250 watt modulators in parallel, which modulated two 250 watt oscillators also connected in parallel. The oscillating circuit and the antenna circuit are described by Mr. Cornish in another paper. Such was the original station and continually since that time a process of evolution has been going on. Many changes were made before the writer became connected with the station and unless they are of particular importance and still incorporated in the station they will not be consideredhere.

THE BEAT FREQUENCY OSCILLATOR.

Shortly after commencing these tests, the necessity of having some method of supplying a variable audio frequency sine wave of known frequency and containing a very small percentage of harmonics was realized. For this purpose a beat frequency oscillator was constructed.

Two oscillators, one fixed and the other variable, are coupled by means of two pick up coils. The difference in the frequencies generated, gives rise to a beat note which is detected and then amplified by means of a resistance coupled amplifier. (See Fig. #2). The circuit is similar to that used in the General Radio Company's Beat Frequency Oscillator.

The fixed circuit A was built to oscillate at approximately 50,000 cycles. The condenser C_1 has a capacity of .0025mfd. The inductance L_1 composed of 154 turns of #18 D.C.C. copper wire in 4 layers on a 10 cm. diameter tube has a value of approximately 4.05 millihenries. L_2, the grid coil has 34 turns of the wire wound on top of L_1. Its value is about 0.9 mh. The pickup coil L_3 has 18 turns also #18 wound outside of the other two.

The second and variable oscillator has a coil exactly the same as the above. The condenser branch shown in detail

in figure #2 consists of a fixed condenser C_2 (.0025mfd) permanently connected in the circuit and paralleled by a 43 plate variable condenser (.001mfd) C_3. Another fixed condenser C_4 (.0004mfd) can be cut in or out of the circuit to change the range of the instrument.

In the resistance coupled amplifier the values of the constants are as follows.

r_1	25,000 ohms
r_2	0.5 megohms
r_3	60 ohms
r_4	100 ohms

The volume control r_5 is a 50,000 ohm commercial unit used commonly in radio receivers. C_5 and C_6 are 1 mfd each.

UX-201-A tubes are used throughout.

The coils in the oscillators are set at right angles to each other to prevent interaction.

LINES FROM STUDIO TO STATION.

1. Measurement of Impedance.

In order that the transmission of varying currents may be carried on with a minimum of distortion, an amplifier must be fed into the transmission line through a matching transformer. Looking at Fig. #3 the matching transformer is choosen so that its impedance looking from A towards B when the line is connected is equal to that of the output circuit of the amplifier. The impedance looking from B to A when the amplifier is connected must be equal to that of the line.'

This principle applies whenever two circuits are joined together and thus another transformer must be used where the line feeds into the speech amplifier. Since our transformers at both ends were bought for a 500 ohm line we decided to measure the characteristic impedance to see how it compared with this value.

The impedances of the line open and shorted were measured with an input frequency of 1000 cycles. The characteristic impedance therefore equals

$$Z_k = \sqrt{Z_{open} Z_{short}} \quad ''$$

' It should be noted here that this matching is not very critical and a difference 2x or 3x will not produce noticeable. distortion.

'' For further explanation see McIlwain and Brainerd "High Frequency Alternating Currents" Chapter X.

Table #1.

Frequency	Comparative Attenuation
100	0.0
350	0.0
670	0.0
1100	0.0
1400	0.0
2000	0.0
2600	0.0
3200	0.0
3700	0.0
4100	-0.1
4600	-0.1
5000	-0.1
7000	-0.1

Explanation: In the table the readings have been adjusted so that the reading for any given frequency represents its attenuation when compared with the attenuation of a 100 cycle note.

The reading for the frequency of 7000 cycles is only approximate because the oscillator is not calibrated accurately for such high frequencies.

the power levels being measured by two General Radio Company Level Indicators Type 586-A. The results obtained on Line #1 are shown in Fig. #5 and Table #1. Line #2 gave almost identical characteristics so they are not shown here. The change in transmission level from about 60 cycles to 7000 cycles is in the neighbourhood of 0.5 decibels, which is well within the range allowable for good transmission of sound.'

VOLUME CONTROL AND INPUT TRANSFORMER.

The General Radio Volume Control Type 552-TC was on order at the time of making these tests and has since been installed. Curves were therefore not taken on it but it is guaranteed by the makers to have a flat frequency response.

The Jenkins and Adair Input Transformer is also of standard make and its frequency characteristic curve is assumed flat since we have no equipment capable of testing it. Some readings were taken using the volume indicators as explained above but it was found that they put too much load on the output sides of the transformers and spoiled the voltage regulation to such an extent that the readings were of no value.

' The db or decibel is the unit used in measuring power level drops and is choosen so that 1 db is the smallest change which can be detected by the ear.

THE SPEECH AMPLIFYING TUBE AND ITS COUPLING CIRCUIT.

A short digression is made here to outline the different types and classes of amplifiers so that the part following will be clearer. In all of the discussion we will confine ourselves to the triode since that is the only type of tube used in the station.

As is well known the triode consists of three elements, one of which, the cathode or filament, supplies electrons, another the anode or plate, usually placed around the filament and to which the electrons flow, and the third a modifying electrode called the grid and placed in the space between the other two. The latter modifying electrode is made in the form of a mesh or grid so that it will not physically interrupt the flow of electrons from the filament to the plate. The plate current may be changed considerably however by varying the potential applied to the grid.

In the diagram shown in Fig. #7 arrangements are

made for measuring the grid bias voltage E_g, the plate voltage E_b and the plate current I_p. If E_b is kept constant at, say the rated voltage of the tube, and E_g is varied, a graph of plate current against grid voltage may be obtained similar to Fig. #8. It will be noted that over the straight portion of the curve equal increments of change of grid potential produce equal increments of change of plate current. For this reason the plate current wave will be a true image of the grid voltage wave producing it provided that none of the swings of grid voltage go over to the curved ends of the graph. When a vacuum tube is operating under these conditions it is said to be a Class A amplifier. Class A amplifiers are used in most receiving circuits on account of the fact that they give true reproduction and also have the largest possible voltage amplification.'

On the other hand, when amplifiers are used in transmitters it is generally desirable for the sake of efficiency to obtain a larger output than is possible from Class A amplifiers. This high efficiency of conversion from from direct to alternating current is obtained when the plate current is stopped during part of the cycle.

' Because the slope of the gurve is greatest at the straight part.

To illustrate why the above statement is true consider the circuit of Fig. #9., which is a typical Class B or Class C radio frequency amplifying circuit. If we want to keep the system L C in oscillation it is only necessary to supply intermittent pulses from the D.C. source E_b. The controlling of these pulses is done from the grid circuit. As mentioned before it is desirable that the conversion from direct current in the E_b circuit to alternating current in the L C circuit should occur with as little loss as possible in the tube. The loss in the tube is the average of the product of the instantaneous plate current and the instantaneous plate voltage. This loss may be reduced first by making the plate current flow in impulses and second by making these impulses occur at times when the plate voltage is a minimum.

Fig, #10 shows how these currents and voltages vary with time in the circuit of Fig. #9. The plate current only flows when the plate voltage is on the minimum half of its swing. In order to make the current flow during half the cycle only the grid bias must be adjusted to point a in Fig. #8. This is called Class B amplification.

If the bias is made even more negative than point a Fig. #8, the flow of plate current will be for smaller periods still and the amplifier is then known as Class C. (See Fig. #11.) '

With the above explanation of Class A, B, and C amplifiers we will now consider the methods of using more than one tube in order to increase the amplification over that which can be obtained from one tube alone. There are many of these methods of coupling tubes but only two will be described here since they are the only ones which have been used in the part of the station with which this report is concerned.

Transformer Coupling

In the circuit shown in Fig.#12, assume an alternating voltage $e_g = E_g \sin \omega t$ (effective value E_g') is applied to the grid of tube #1. The amplification factor of the tube being , the corresponding alternating plate voltage may be written E_g'. This voltage causes a current to flow in the primary of the transformer generating in its secondary a voltage E_g''. This voltage is applied to the grid of tube #2 and is amplified through this tube appearing in the plate circuit as E_g''. On account of the fact that the transformer

' See Everitt, Communication Engineering, p. 361 et seq.

may have a step up ratio of voltages the total amount of amplification is in creased in the system.

Impedance Coupling.

The other form of interest at this time is impedance coupling. See Fig.#13. This is probably the most general type of coupling used in broadcasting stations for the speech amplifying system.' The variable plate current flowing through the impedance Z causes a voltage drop across it which is applied through the condenser C to the grid of the following tube. This condenser also prevents the plate supply of the first tube from applying a positive potential to the grid of the second tube. The grid leak resistance R is inserted to provide a a direct connection between the grid and filament of the second tube, preventing the grid from accumulating a positive charge and thus blocking its action.

The Speech Amplifier and its Coupling.

We are now in a position to discuss the speech amplifying system of the station. The original connections are shown in Fig. #12.

Mutual characteristic curves of the R-211-D tube were first taken for values of 785 and 900 volts on the plate. These curves are shown in Fig.#15.

' The impedance coupled amplifier is much flatter in its frequency response curve than transformer coupled amplifiers. It does not give as great amplification though.

The tube had been operating at a plate voltage slightly under 785 and the normal plate current was about 20 milliamperes. The normal operating point was therefore the point (a) Fig. #15. Thus instead of being on the straight portion of the curve it was around the lower bend. This must then have been the cause of considerable distortion in the amplified signal. In order to improve this condition the plate voltage was increased to 900 and the bias changed to - 45 volts. The operating point was thus changed to point (b) Fig, # 15. Under these conditions a grid swing of about 7 volts can occur without getting appreciably off the straight portion of the curve.'

With regard to the frequency characteristics of the speech amplifying system little can be said. Here again we were unable to take measurements with any degree of accuracy. We decided to change from the transformer to impedance coupling, however, because it is usually possible to get a better frequency response curve from the impedance coupling. The connections are shown in Fig. # 13 and the values are as follows, Z = 40 mh, R = 25,000 ohms, and C = 1 mfd.

'That this tube is not particularly suited for Class A amplification is quite apparent from its characteristic curves. If however the grid swing is kept down to about 7 volts there will be no distortion.

THE MODULATING SYSTEM.

Thus far we have traced through the audio frequency section of the radio station. It is impossible to broadcast these audio frequency waves as they are for two reasons.

1. At such low frequencies (100 to 10,000 cycles) the radiated energy is very small.

2. Even if there were enough energy in the radiated audio wave, the air would be so congested that the results received would be unintelligible.

For these reasons the audio signals are superimposed on a carrier of much higher frequency,(in this case 580 kilocycles).

In order that intelligence may be transmitted over a radio frequency wave, it is necessary in some way to have this wave contain components which can be singled out at the receiving station to reproduce the original signal.

Let us assume that we have a constant amplitude carrier of frequency f_c. An audio signal of frequency f_s is to be transmitted along with it. These two waves are superimposed by means to be described later and the resulting wave form is shown in Fig. #18.

A simple analysis of this complex wave is as follows.

At any time t,

$$e = E_o + mE_o \sin 2\pi f_s t$$

where E_o is the amplitude of the carrier frequency alone, and m, the percentage modulation' in other words the ratio E_s/E_o.

Knowing this amplitude we can now write the equation for the modulated wave as follows,

$$e = E_o(1 + m\sin 2\pi f_s t) \sin 2\pi f_c t$$

$$= E_o \sin 2\pi f_c t + mE_o \sin 2\pi f_s t . \sin 2\pi f_c t$$

which by expanding the second term becomes

$$e = E_o \sin 2\pi f_c t + \frac{mE_o}{2} \cos 2\pi(f_c - f_s)t - \frac{mE_o}{2} \cos 2\pi(f_c + f_s)t$$

These three terms in the last equation are explained as follows,

1. The fundamental or carrier $E_o \sin 2\pi f_c t$.

2. The upper side band $\frac{mE_o}{2} \cos 2\pi(f_c + f_s)t$, with a frequency of the fundamental plus the signal.

3. The lower side band $\frac{mE_o}{2} \cos 2\pi(f_c - f_s)t$, with a frequency of the fundamental minus the signal.

The two side bands are alike in all respects except frequency and they are the parts of the complex transmitted wave which carry the intelligence.

'Note that the percentage modulation or the degree of modulation as it is sometimes called can never be over 100% but may have any value lower than this.

When a voice signal is to be transmitted we have, not a constant amplitude of frequency f_s as shown in the above calculations but a very complex wave containing many frequencies in the range 100 to 15,000 cycles![1] The signal wave could be analysed by a Fourier's series and the resulting sine waves combined with the carrier as shown above. All these could then be superimposed to give the ultimate form of the transmitted wave.

From the above discussion, the following points arise, If it is to be possible to receive the transmitted intelligence exactly as it was applied to the carrier wave;

1. All the frequencies in the signal must be contained in the side bands at amplitudes relative to their amplitudes in the signal.

2. There must be no extraneous frequencies added.

3. They must arrive at their destination in proper phase relation with one another.

If (1) above, does not hold there is said to be frequency distortion. This type of distortion is not distinctly noticable to the ear providing the power of any particular component is not reduced to less than 70% of its former value.

[1] It has been found that in order to get good reproduction of the original it is only necessary to transmit the frequencies from 100 to 8000 cycles.

The second, non-linear or amplitude distortion, may be looked on in another way. If the amplitude of the signal received is not directly proportional to the amplitude of the input, new frequencies have been introduced which are multiples of harmonics of the original,' This is very easily detected by the ear and should be kept as small as possible.

The third, called phase distortion, is of comparatively little importance since it is only noticed when the phase shifts are very large.

These are the requirements for good transmission of sound and we will now see how the method of modulation used in the station fulfils them.

The Heising system or plate modulation is shown in Fig. #19. The signal waves from the speech amplifier are impressed on the grids of three 250 watt power tubes connected in parallel. The plates of these three power amplifiers or modulators are connected to the plates of the Class B, "push pull" radio frequency amplifiers. The audio frequency signal wave causes the plate supply voltage of the radio frequency amplifiers to take the form of a constant D.C. applied voltage with an audio frequency voltage impressed on it.

'For an explanation of this see Everitt "Communication Engineering" p. 406 et seq.

This is shown in Fig. #20(a). The radio frequency applied to the grids of the R.F. amplifiers is of constant amplitude and is shown in Fig. # 20(b). The curve marked cutoff grid bias is interpreted as follows. The cut off when the plate voltage is at its normal value is shown by the straight part of the dotted curve. When the plate voltage starts to vary on account of the impressed e.m.f. of the modulator tubes the grid cut off then varies as shown by the rest of the curve. Therefore plate current only flows when the grid impressed e.m.f. lies above the dotted curve. The effective plate voltage will therefore follow a curve as shown in Fig. # 20(a). The plate current resulting from this will be similar to Fig. # 20(c). and the current in the tank circuit will be represented by Fig. # 20 (d). Is this enveloped carrier the proper form to give a true reproduction of the original signal?

Assuming that the modulators give a true image of the audio frequency, the curve in Fig. # 20(a) will also be a true image. The plate current curve Fig. # 20(c) will also have an envelope of the same configuration but is only on the positive section of the graph. The individual

positive swings of R.F. current give impulses to the tank circuit and keep it oscillating, the amplitude of the oscillations depending on the amplitude of the impulses given therefore follows the same curve as the original signal.

In the station, Fig. # 19, a 625 ohm resistance is connected in the plate supply line between the modulators and the R.F. amplifiers in order to cut the amplifier plate voltage down. This resistance is by-passed by a 4 mfd. condenser so that it will allow the audio frequency from the modulators to get through with very little drop. The two radio frequency chokes in parallel prevent the high frequency oscillations in the tank circuit from backing up into the modulators.

It should be noticed that since all the intelligence is in the side bands it is desirable to have the factor m as high as possible. The swing of the carrier amplitude must therefore be as large as possible and this swing must occur without introducing distortion. The measurement of percentage modulation is therefore important and may be carried out in a number of ways.

MEASUREMENT OF THE MODULATION FACTOR.

The method used most successfully in the station is described by C.B.Jolliffe on page 660 of the 1929 Proceedings of the Institute of Radio Engineers. It used the electron tube voltmeter, the connections being shown in Fig. 21.

The operation of the voltmeter is as follows. Without any radio frequency applied set R_1 at zero (i.e. at A) and then adjust R_2 until the plate current milliammeter just fails to show a reading. Now apply the unmodulated carrier wave and then adjust R_1 until the plate meter again just fails to read. The voltage shown on the voltmeter at this point is V_1 and represents the peak value of the unmodulated wave. Modulate the carrier and find another value of voltage such that the milliammeter again just fails to read. This is V_2.

Since the currents are proportional to the voltages the percentage modulation is then given by

$$\%\ \text{modulation} = \frac{V_2 - V_1}{V_1} \times 100$$

For different settings of the power level indicator the following results were obtained. See Table # 2.

Table #2.

Power Level	I_r	I_r mod.	m
-6 db	11.6	14.7	28%
-4 db	11.6	15.2	31%
-2 db	11.6	15.9	37%
+2 db	11.6	18.6	60%
+4 db	11.6	19.5	68%

The readings of power level are taken at the station end of the studio line and cover the range through which the level is allowed to swing during programs.

In the station we can let our level indicator swing to aapproximately -2 db. without causing distortion. At this point we are getting 37% modulation which is very low.'

Since making the changes mentioned in this report we have had many comments from listeners commending the quality of reproduction. That we should have good quality in view of some of the things discussed above may seem strange and is due to the fact that we keep the grid swings on the speech amplifier and the modulators down to comparatively small values.

The result of this, also pointed out above, is that we are not getting a very high % modulation and therefore not carrying much power in our sidebands. With the equipment that we have, and using our present system I think that the station is operating with quite satisfactory results.

The fundamental object in all the work done has been to improve the station from the point of view of the listening public. In many cases where we would have liked

' The modulation was also measured by means of a cathode ray oscillograph and values obtained were about 15% higher tha n those given here.

to do more experimenting it has been impossible because the station had to be kept in operation.

During all the work on the station we have had the cooperation and assistance of Dr. H.J. MacLeod, and to him we would express our thanks.

April 7, 1933.

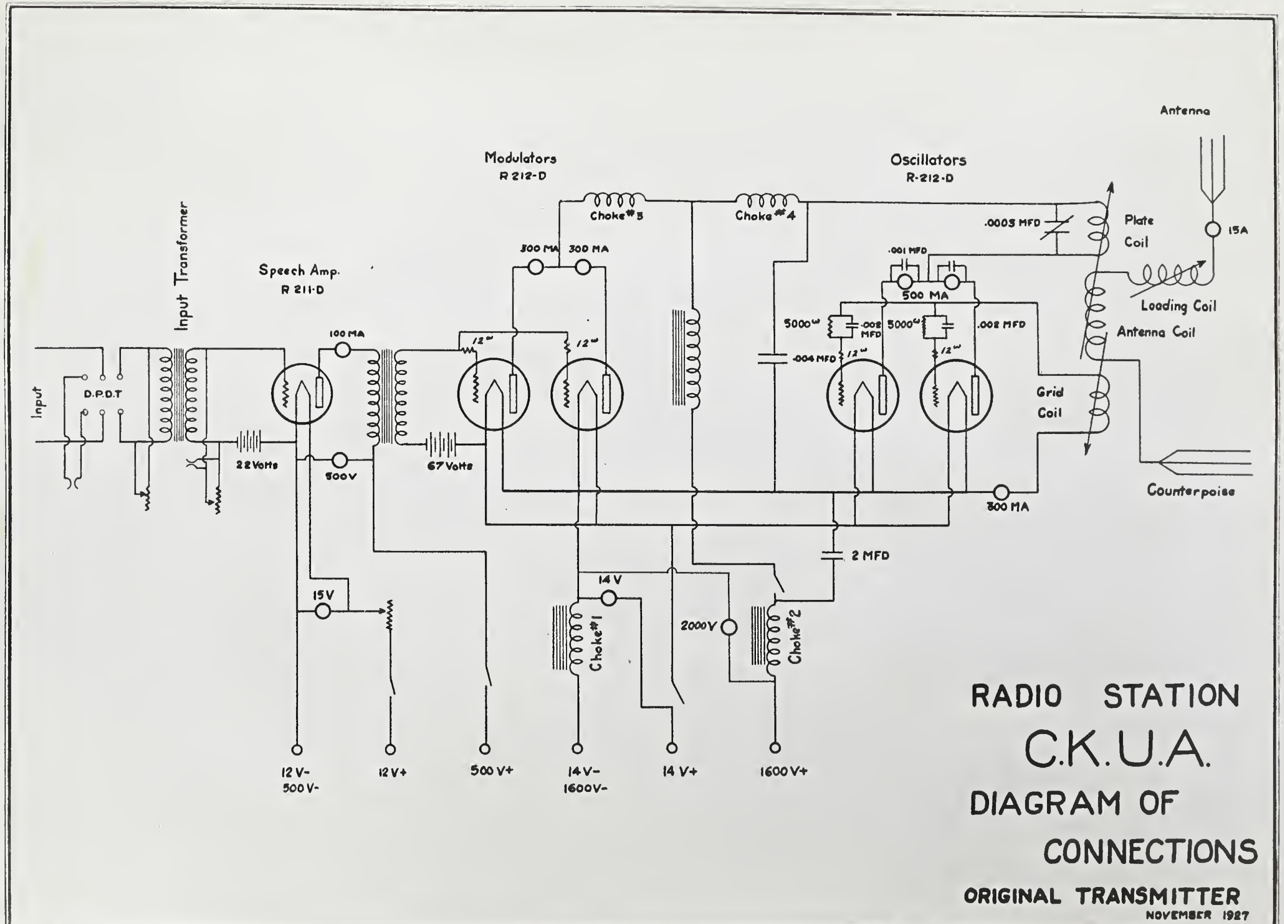
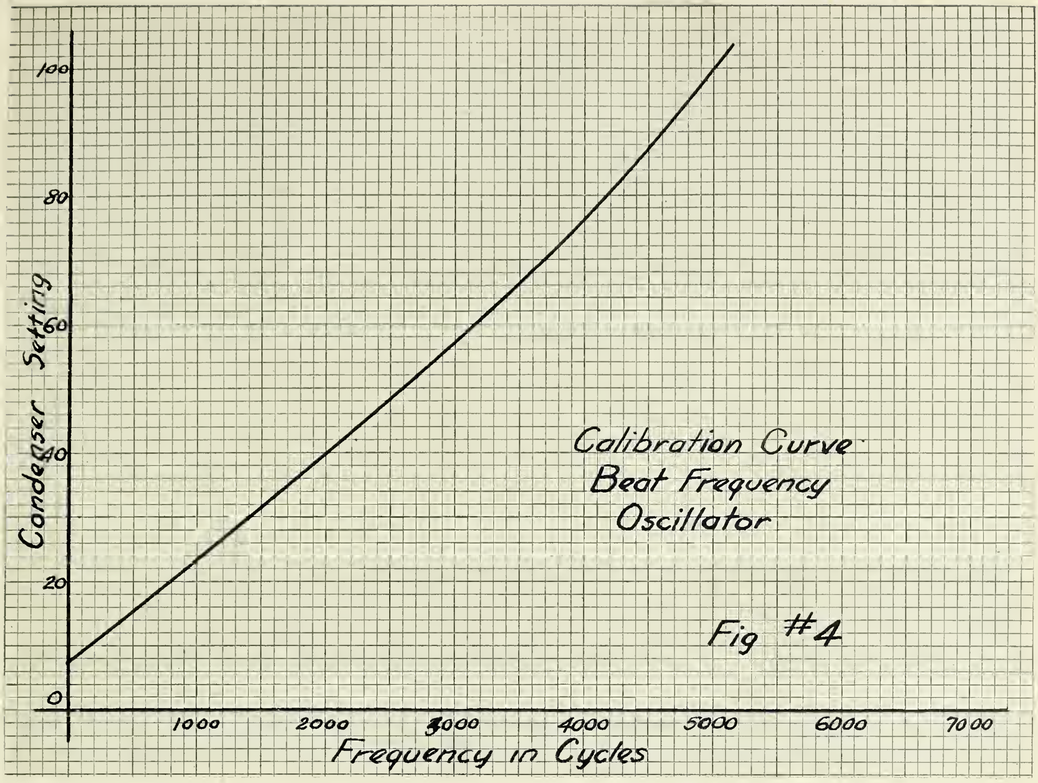

Input
D.P.D.T
Input Transformer
Speech Amp.
R 211-D
100 MA
22 Volts
500V
67 Volts
Modulators
R 212-D
300 MA
300 MA
Choke #3
Choke #4
12"
12"
Oscillators
R-212-D
.0003 MFD
.001 MFD
500 MA
5000ω
.002 MFD
.004 MFD
5000ω
.002 MFD
Plate Coil
Antenna
15A
Loading Coil
Antenna Coil
Grid Coil
Counterpoise
300 MA
2 MFD
15V
14 V
Choke #1
2000V
Choke #2
12 V-
500 V-
12 V+
500 V+
14 V-
1600V-
14 V+
1600V+
RADIO STATION
C.K.U.A.
DIAGRAM OF
CONNECTIONS
ORIGINAL TRANSMITTER
NOVEMBER 1927

Fig. #1



Calibration Curve
Beat Frequency
Oscillator

Fig #4

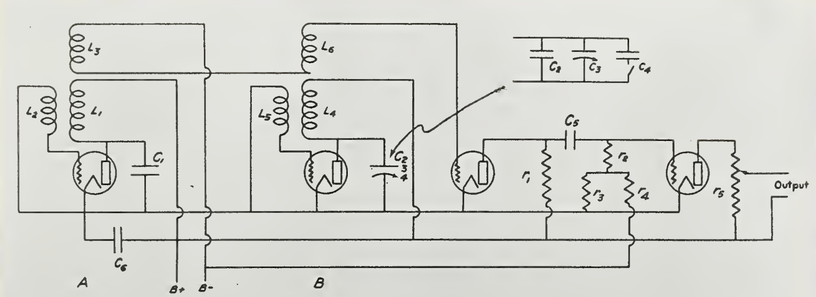


Fig. # 2
Beat Frequency Oscillator

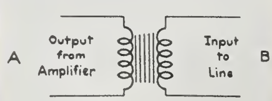
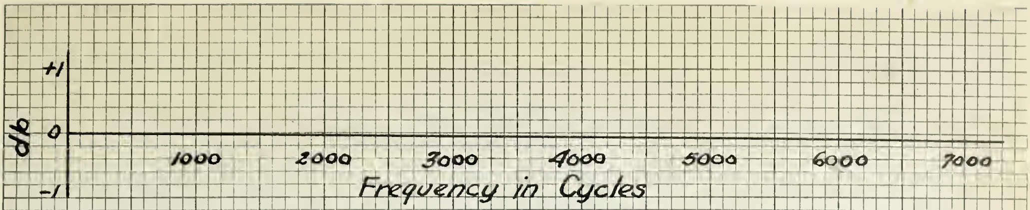


Fig. # 3
Matching Transformer



Comparative attenuation of different frequencies on Line # 1

Fig. # 5

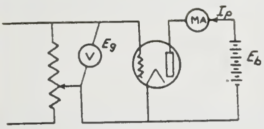


Fig. # 7

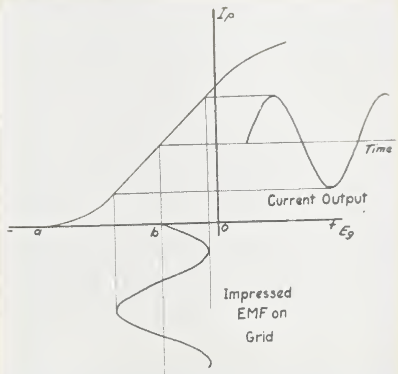


Fig. # 8

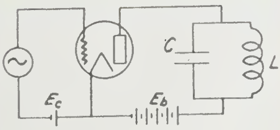


Fig. # 9
Class B and C Amplifier

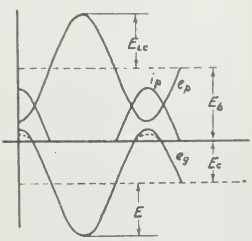


Fig. # 10

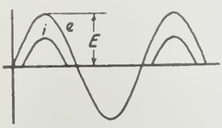


Fig. # 11

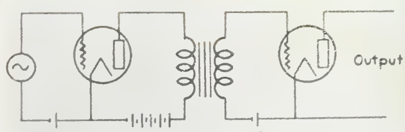


Fig. # 12
Transformer Coupled Amplifier

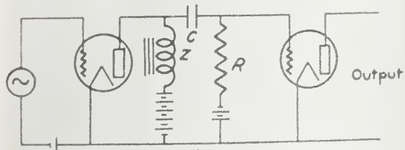


Fig. # 13
Impedance Coupled Amplifier

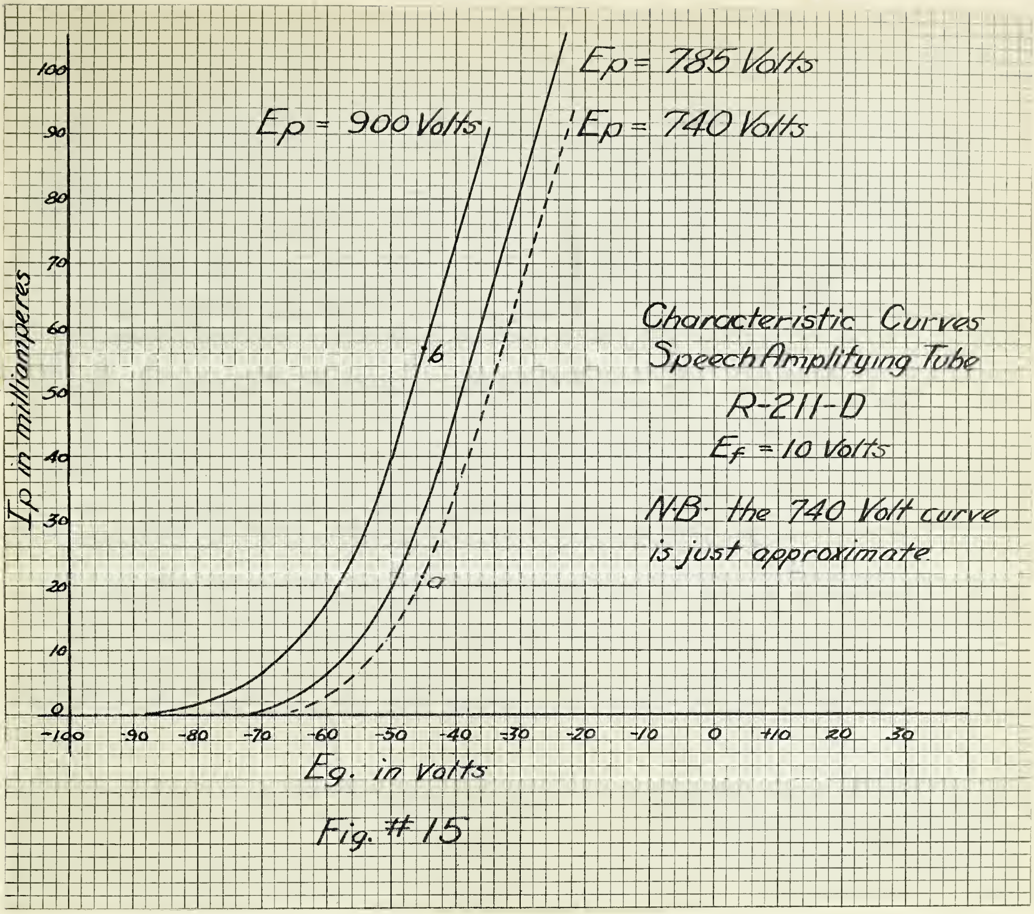

Ep = 785 Volts
Ep = 900 Volts
Ep = 740 Volts
Characteristic Curves
Speech Amplifying Tube
R-211-D
Ef = 10 Volts
N.B. the 740 Volt curve
is just approximate
Ip in milliamperes
Eg. in volts
100
90
80
70
60
50
40
30
20
10
0
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
+10
20
30
b
a

Fig. # 15

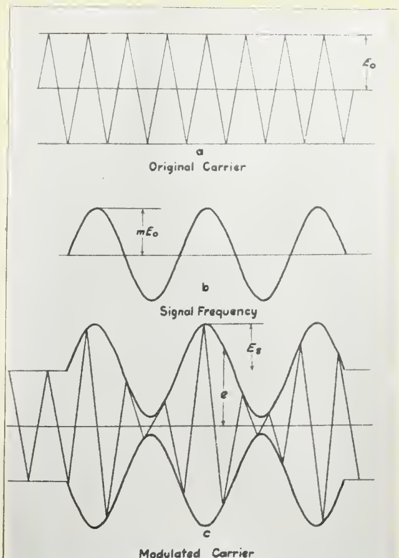

Eo
a
Original Carrier
mEo
b
Signal Frequency
Es
e
c
Modulated Carrier

Fig. # 18

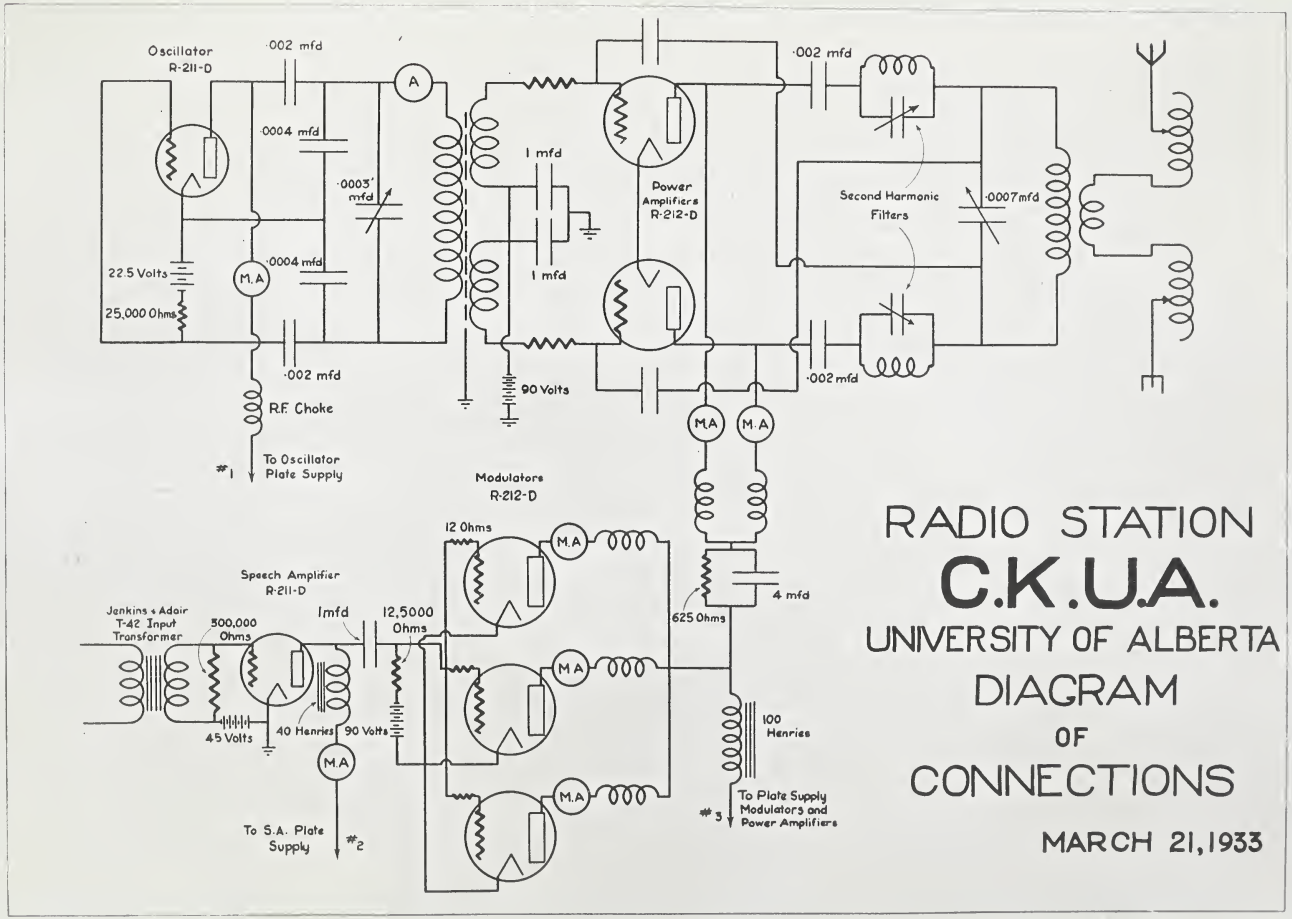

Oscillator
R-211-D
·002 mfd
·0004 mfd
·0003' mfd
·0004 mfd
22.5 Volts
25,000 Ohms
·002 mfd
R.F. Choke
#1
To Oscillator
Plate Supply
A
M.A
1 mfd
1 mfd
90 Volts
Power
Amplifiers
R-212-D
·002 mfd
Second Harmonic
Filters
·0007 mfd
·002 mfd
M.A
M.A
Modulators
R-212-D
12 Ohms
M.A
M.A
M.A
4 mfd
625 Ohms
100
Henries
#3
To Plate Supply
Modulators and
Power Amplifiers
Speech Amplifier
R-211-D
Jenkins + Adair
T-42 Input
Transformer
500,000
Ohms
1mfd
12,5000
Ohms
45 Volts
40 Henries
90 Volts
M.A
To S.A. Plate
Supply
#2
RADIO STATION
C.K.U.A.
UNIVERSITY OF ALBERTA
DIAGRAM
OF
CONNECTIONS
MARCH 21, 1933

Fig # 19

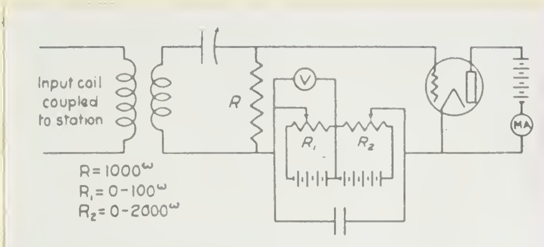

Input coil coupled to station
R
R_1
R_2
MA
$R = 1000^{\omega}$
$R_1 = 0\text{-}100^{\omega}$
$R_2 = 0\text{-}2000^{\omega}$

Fig. #21

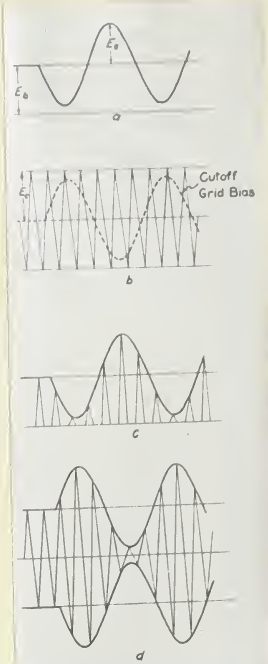
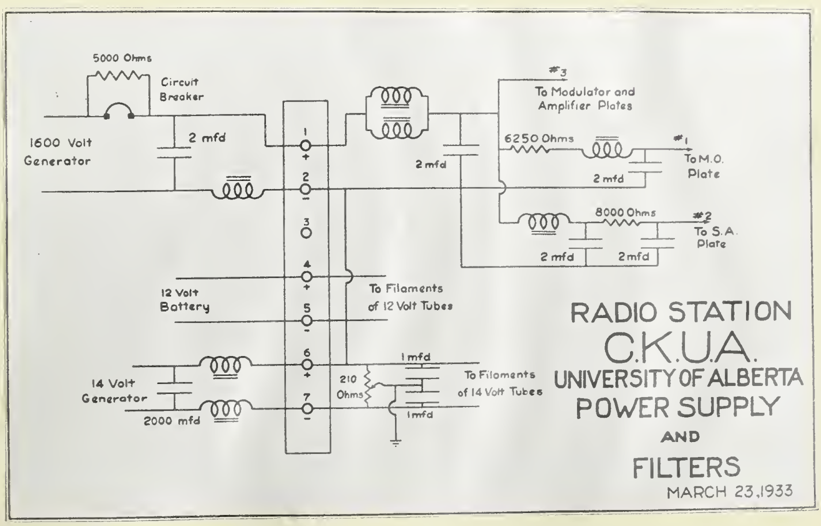

E_s
E_b
a
E_c
Cutoff Grid Bias
b
c
d

Fig. #20


5000 Ohms
Circuit Breaker
1600 Volt Generator
2 mfd
1
2
3
4
5
6
7
#3 To Modulator and Amplifier Plates
2 mfd
6250 Ohms
#1 To M.O. Plate
2 mfd
8000 Ohms
#2 To S.A. Plate
2 mfd
2 mfd
12 Volt Battery
To Filaments of 12 Volt Tubes
14 Volt Generator
2000 mfd
210 Ohms
1 mfd
1 mfd
To Filaments of 14 Volt Tubes
RADIO STATION
C.K.U.A.
UNIVERSITY OF ALBERTA
POWER SUPPLY
AND
FILTERS
MARCH 23, 1933